Contribution of forest fire and land covers to emissions of CO_2, CH_4 and N_2O in Central Yakutia

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1. INTRODUCTION

Boreal forests have been frequently damaged from forest fires. In a boreal forest fire occurred in 1998, the carbon released from the burned area of 17.9 Mha was estimated to be 290-383 Tg C, which accounted for 6.7 - 8.9 % of the global total carbon release from biomass burning. It is also reported that the Russian forest fires accounted for 71% of the total carbon release (Kasischke and Bruhwiler, 2003), which corresponds to Japanese total greenhouse gas emission of 355 Tg C in 2000 (GIO, 2005). Carbon release from the burned area of 1850 ha in 1997 Krasnoyarsk fire was estimated to be 16 Gg C (Isaev et al., 2002) and mean carbon release from 1959 to 1999 in Canadian forest fires was estimated to be 27 Tg C y^{-1} from mean burned area of 2.03 Mha (Amiro et al., 2001). These data suggest that the rate of carbon release from boreal forest fire ranges from 8 to 21 t C ha^{-1} y^{-1}. The values are significantly larger than the net primary production (NPP), which is, for example, 1.23 t C ha^{-1} y^{-1} in average for Siberian forests estimated by Schulze et al. (1999), and also larger than soil respiration, which is 2.73 t C ha^{-1} y^{-1} in average for Taiga soils estimated by Raich and Schlesinger (1992).

Biomass burning emits methane (CH_4) and nitrous oxide (N_2O) as well as carbon dioxide (CO_2). Emissions of CO_2 and CH_4 during the boreal forest fire in 1998 were 828 - 1103 Tg C and 2.9 - 4.7 Tg C, respectively (Kasischke and Bruhwiler, 2003), which are 13 - 18% of CO_2 emission from annual fossil fuel burning and 0.6 - 1.0% for global total CH_4 emission reported by IPCC (2001). The global N_2O emission from biomass burning is estimated to be 0.7 Tg N y^{-1} which accounts for 20% of the global total N_2O emission (Olivier et al., 1998).

Permafrost is a perennially frozen ground which underlies 20 - 25% of the exposed land surface of the earth in regions with cold climates (Serreze et al., 2000). In the permafrost area of East Siberia, when excess ice of permafrost thaws after severe forest disturbance, the surface collapses forming thermokarst, which is called Alas in Siberia (Desyatkin, 1993). This can result in the total destruction of ecosystems or it may convert into other types of ecosystem. Water supplied from the thawing permafrost flows laterally and makes ponds, which could cause trees to die (Osterkamp et al., 2000; Jorgenson et al., 2001). During the process of Alas forming, accumulation of organic matter associated with soil erosion and increase of pH associated with dissolution of carbonates in original soil proceeds (Desyatkin, 1990). Then development of wetland ecosystem makes peat. Net ecosystem production of a boreal wetland was estimated to be 430 - 620 kg C ha^{-1} yr^{-1}, which corresponds to those of forests (Schulze et

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al. 2002). When ponds dry up gradually, salts accumulate in the soil, and grassland dominated by salt-tolerant species develop (Desyatkin, 1993).

Forest soils generally uptake CH_4 (King, 1992), contributing to approximately 10% of the global CH_4 decomposition (IPCC, 2001). However, forest disturbance is generally considered to decrease the CH_4 consumption activity of soil (Dobbie et al., 1996). Alas formation after forest disturbance increases CH_4 production and decreases CH_4 consumption due to increase in soil moisture, salt concentration and organic carbon content in Alas soil (Morishita et al. 2003).

Alas may be considered as a land stimulating N_2O emission. Microbiological processes of nitrification and denitrification regulate the production and consumption of N_2O (Sahrawat and Keeny, 1986). Lety et al. (1980) reported that increasing soil moisture increased N_2O emission from the soil. Aulakh et al. (1992) reported that pH and organic carbon content in soil were important regulators of denitrification.

Sawamoto et al. (2000) and Amiro et al. (2003) suggest that soil respiration generally decreases following boreal forest fire due to mainly decrease in root respiration. However, concerning soil organic matter decomposition, both its decrease and increase have been observed. Decrease in soil organic matter decomposition after forest fire was probably caused by decreased microbial population and less carbon substrate (Fritze et al., 1994). On the other hand, the increase in soil organic matter decomposition was probably due to rise in temperature with increase in direct heat on ground surface and rise in soil moisture with decrease in plant water uptake (Sawamoto et al., 2000). Johnson (1992) concluded that low-intensity burns had very little effect on soil respiration. Although organic matter content in Alas might increase during the process of pond formation, the accumulated organic matter may decrease during pond drying if grass production is lower than organic matter decomposition.

The purpose of this study is to clarify the source and sink of CO_2, CH_4, and N_2O in a permafrost area in East Siberia. We estimated their contributions in major land covers such as forest, grassland, and pond and during the forest fire in Central Yakutia.

2. MATERIALS AND METHODS

2.1 Carbon release during the forest fire

Conard et al. (2002) classified the forest fires in Siberia as following three types: low-intensity surface fires, moderate-intensity surface fires and high-intensity crown fires. Fuels for fire were defined as understory vegetation, litter layer, and aboveground biomass. The carbon release rates from these fuels are estimated as follows: 50% of understory vegetation carbon and 10% of litter layer carbon in the low-intensity; 90% of understory vegetation carbon and 50% of litter layer carbon in moderate-intensity surface fires; and 100% of both understory vegetation and litter layer carbon and 40% of above ground carbon in high-intensity crown fires. Using these values and average of biomass densities of aboveground vegetation and forest floor fuels in Siberian forests, carbon release density from each types of fire was estimated as follows: 2.3 t C ha^{-1} for low-intensity surface fires, 8.6 t C ha^{-1} for moderate-intensity surface fires, and 22.5 t C ha^{-1} for high-intensity crown fires.

Furthermore, Conard et al. (2002) defined burning conditions as severe and moderate burning conditions in the combination of three types of fire. In the case of severe burning condition, the contribution of low-intensity surface fire, moderate-intensity surface fire and high-intensity crown fire is made 20, 30 and 50%, respectively, while in the case of moderate burning condition, it is made 20, 60 and 20%, respectively. Finally, they provided 10.1 t C ha^{-1} for moderate burning condition and 14.3 t C ha^{-1} for severe burning condition. Average value of carbon release during fire was estimated to be 12.2 t C ha^{-1}. Measured value of carbon release from the burned forest in Yakutsk was compared with these values.

In order to understand the forest fire conditions in Central Yakutia, a survey was conducted at a burned forest which was located at 52 km south-west from the center of Yakutsk city through the road to Vilyuyskiy (N62^o 03', E 129 ^{o} 49') in the middle of July 2002. It was 50 years old Larch (*Larix gmelinii*) forest with 18000 stands per ha, 5.0 m in height and 3.5 cm in diameter at breast height. The forest fire started in early May 2002, then it was extinguished in mid-August of the year. At the burning place, the forest floor was smoldering and tree trunks were scorched. There was also a place where whole tree was burned. Therefore, it seemed that ground fire occurred first, then fire spread to trees and the whole trees were burned.

Soil samples were taken from the intact forest and burned places. Each of nine samples of understory vegetations and litter layer in intact forest was taken from 10 cm × 10 cm area. Samples of organic horizon in the intact forest and burned places were taken into steel cylinder at nine and 27 replicates, respectively. These samples were weighed and the moisture content was measured using sub-sample in order to estimate dry bulk density. Others were air-dried. After the air-dried samples were brought back to the laboratory of Hokkaido University in Sapporo, Japan, the samples were ground and used to measure total carbon by dry combustion method using a CHN-analyzer equipped with a thermal conductivity detector (Vario-EL, Elementar Americas, Inc., USA). The amount of carbon release from forest floor fuels burning was estimated as a difference between the total amount of carbon contents in the intact forest and burned places.

Total amount of carbon release is estimated as the sum of carbon release from aboveground biomass burning and forest floor fuels burning. The carbon release from aboveground biomass burning of this study site was estimated to be 5.5 t ha^{-1} as the product of the biomass density of aboveground vegetation (30 t ha^{-1} by Shibuya et al., 2004), the carbon content of the aboveground vegetation (0.45 by Kasischke and Bruhwiler, 2003) and the combustion efficiency of the aboveground vegetation (0.4 by Conard et al., 2002).

2.2 Gas concentrations in smoke

Six cylindrical steel chambers, 25 cm in height and 20 cm in diameter, were set up on smoldering ground surface and smoke samples were taken into 1 L Tedlar bag at 2 min after setting up of chamber, because the temperature inside the chamber increased very quickly as it was over 80 °C after 5 min from the set up of chamber. A 300 mL gas sample was taken from a chamber into a 1 L Tedlar bag. The sample was used for determining CO_2 concentration. In order to keep quality of the sample for measuring CH_4 and N_2O concentrations, each 20 mL of air sample taken into Tedlar bag was transferred into 10 mL brown colored glass bottles within the same day of sampling. CO_2 concentrations were determined by using infrared portable CO_2 analyzer (ZFP9, Fuji Electronics Co. Ltd., Japan) within a day after sampling. After the gas samples in 10 mL glass bottles were brought back to the laboratory of Hokkaido University in Sapporo, Japan, CH_4 concentrations were analyzed with FID gas chromatograph (Shimadzu GC-8A, Shimadzu, Japan) and N_2O concentrations with ECD gas chromatograph (Shimadzu GC-14B, Shimadzu, Japan). The detection limits were 2 ppmv for CO_2, 0.01 ppmv for CH_4, and 0.002 ppmv for N_2O.

2.3 Calculation of gas emissions during the forest fire

The emission ratio of CH_4/CO_2 (gC/gC) and N_2O/CO_2 (gN/gC) was calculated by using the gas concentrations of samples taken at the burning place. For emission ratio of CO/CO_2, we used 0.213 gC/gC, which was the mean value measured during smoldering fire in boreal forest (Cofer et al., 1991; Cofer et al., 1998), due to no measurement of CO concentration in this study. It is assumed that carbon release during fire equals the sum of carbon from CO_2, CH_4 and CO according to carbon from these three gases accounted for more than 99% of carbon release during the forest fire (Lausen et al., 1992). Therefore, gas emissions during the forest fire were calculated as follows:

CO_2 emission = carbon release during fire / (1+CH_4/CO_2 + CO/CO_2)

CH_4 emission = CO_2 emission during fire × CH_4/CO_2

N_2O emission = CO_2 emission during fire × N_2O/CO_2

2.4 Gas emissions from land covers

Landscape of Yakutsk region is characterized by forests, grasslands, and ponds. Grassland is commonly divided into wet and dry types. In order to estimate gas emissions from the land covers, we used the data of annual CO_2, CH_4, and N_2O emissions measured in an Alas and adjacent forest in Neleger (N62°19', E129°30'), which is located at 30 km north-northwest from the center of Yakutsk city (Takakai et al. in this issue; Sawamoto et al., 2003). The gas emission data were compared with the literature values of boreal areas.

2.5 Global warming potential

The global warming potential (GWP) was calculated by using a 100-year time horizon recommended by IPCC (2001), and the factors of 23 for CH_4 and 296 for N_2O were used.

GWP_{CO2} (kgCO_2 ha^{-1}) = CO_2 (kgC ha^{-1}) ×(44/12)

GWP_{CH4}(kgCO_2 ha^{-1}) = CH_4 (kg C ha^{-1}) × 23×(16/12)

GWP_{N2O} (kgCO_2 ha^{-1})= N_2O (kg N ha^{-1})×296×(44/28)

where GWP_{CO2}, GWP_{CH4}, and GWP_{N2O} are GWP due to CO_2, CH_4, and N_2O emissions, respectively.

2.6 Classification of land cover and estimation of gas emissions

Images from LANDSAT ETM7+ (dated 27 August 1999 and 30 October 1999 and area of 2604 km^2) near Yakutsk city were used to classify the land cover. Yakutsk city, Rena river and its riparian zone were excluded from the analysis to evaluate forest area only. The land cover of the images was classified into forest, grassland, open water, and others (almost road). Open water was identified as pixels with digital number (DN) less than 27 in band 5 of the August image. In other pixels, grassland was identified as pixels with DN larger than 88 in band 2 of the October image. In other pixels, forest was identified as pixels with NDVI (= (Band 4 - Band 3) / (Band 4 + Band 3) larger than 0.2. Other pixels include burned area and town. However, wet grassland was estimated by using the high resolution satellite image. Accuracy of this classification was calculated as follows. One hundred classified pixels were chosen randomly from each land-cover type of the initial classification result from the LANDSAT image as reference pixels. Then high-resolution satellite images, aerial photographs, topographical maps, and ground truthing were used to ascertain the actual land covers. The accuracy of the classification was calculated by dividing the total number of correctly classified reference pixels by the total number of reference pixels. The area of each type of land cover was calculated by multiplying the number of identified pixels by 0.0009 km^2 pixel^{-1}.

The forest fire occurred in Yakutsk in 2002 burned 50279 km^2 which corresponds to 1.62 % of the whole land area of Yakutsk (IFFN, 2003). The burned area within 2604 km^2 was estimated by using the proportion value. Gas emissions were calculated by multiplying each land area by the mean gas fluxes for each land-cover type and fire.

3. RESULTS AND DISCUSSION

3.1 Carbon release during the forest fire in 2002

Amounts of organic carbon in forest floor fuels (understory vegetations, litter layer, and organic horizon) in the intact forest and burned places are shown in Table 1. The intact forest had the organic carbon of 17.8 t C ha^{-1} while burned soils significantly decreased the organic carbon to 8.7 t C ha^{-1}. Therefore, 9.1 t C ha^{-1} was released during the forest fire, which was similar to 8.6 t C ha^{-1} in moderate-severity surface fire (Conard et al., 2002). An apparent combustion efficiency of the organic carbon was 51%. The value was similar to that for moderate-intensity surface fires proposed by Conard et al. (2002).

As mentioned above, the carbon release from above ground biomass burning in this site was estimated to be 5.5 t C ha^{-1} Therefore, total carbon release during fire was estimated as 14.6 t C ha^{-1}. But, it was smaller than 22.5 t C ha^{-1} of carbon released from high-intensity crown fire (Conard et al., 2002). However, the maximum biomass density of aboveground vegetation in Central Yakutia is reported to be 100 t ha^{-1} (Shibuya et al., 2004). Using this value, the maximum amount of carbon release from aboveground biomass burning is estimated as 18 t C ha^{-1}. Therefore, the total carbon release during fire is estimated as 27 t C ha^{-1}, which is similar to the high-intensity crown fire reported by Conard et al. (2002).

From these comparisons, we judged that the estimation by Conard is reasonable to use the carbon release during fire in Central Yakutia.

Table 1. Amount of organic carbon in intact forest and burned place 2 months after the forest fire in 2002 near Yakutsk.

	Organic C (kgC ha^{-1})								
	Understory vegetation		Litter layer		Organic horizon		Total		
	mean	se	mean	se	mean	se	mean	se	*
Intact forest	1122	78	5970	496	10668	876	17760	388	a
Burned place					8714	1536	8714	1536	b
Difference							9046	1584	

*Same letter indicates no significant difference at 5 % level.

3.2 Gas emissions during fire

Table 2 shows the concentration of CO_2, CH_4, and N_2O in smoke released from burning of forest floor fuels during the forest fire in 2002. The CO_2, CH_4, and N_2O concentrations were 43, 66, and 12 times as high as those in intact air, respectively. Emission ratio of CH_4/CO_2 was 0.00742 gC/gC and of N_2O/CO_2 was 0.000541 gN/gC. As shown in Table 3, emission ratios have been reported to be the difference between ground surface fire and crown fire in boreal forest (Cofer et al., 1991; Cofer et al., 1998). Therefore, the average values of the emission ratios for both types of fire were used to estimate CO_2, CH_4, and N_2O

Table 2. Concentration of gases in smoke released from burning of forest floor during the forest fire in 2002 near Yakutsk.

	Unit	mean	se
CO_2	ppmv	15813	3416
CH_4	ppmv	116	27
N_2O	ppmv	3.9	1.7
CH_4/CO_2	gC/gC	0.00742	0.0009
N_2O/CO_2	gN/gC	0.000541	0.00017

emissions during fire. The gas emissions from crown fire, moderate-severity surface fire and low-severity surface fire were calculated by using the carbon release values of 22.5 t C ha^{-1} for crown fire, 8.6 t C ha^{-1} for moderate-severity surface fire, and 2.3 t C ha^{-1} for low-severity

Table 3. Emission ratios in different types of boreal fire.

Type of fire	Location	n	CO/CO_2 gC/gC	se	*	CH_4/CO_2 gC/gC	se	*	N_2O/CO_2 gN/gC	se	*
Ground fire	Yakutsk†	6				0.0076	0.0009	b	0.00054	0.00017	a
	Canada‡	13	0.121	0.019	bc	0.0121	0.0032	ab	0.00021	0.00005	a
	Siberia※	4	0.335	0.045	a	0.0130	0.0020	ab			
	Canada※	5	0.185	0.014	b	0.0140	0.0020	a			
	Average		0.214	0.051	ab	0.0117	0.0044	ab	0.00038	0.00018	a
Crown fire	Siberia※	5	0.113	0.027	bc	0.0040	0.0010	c			
	Canada※	10	0.094	0.010	bc	0.0040	0.0020	bc			
	Canada‡	78	0.067	0.012	c	0.0064	0.0020	abc	0.00018	0.00005	a
	Canada‡	14	0.115	0.021	bc	0.0112	0.0031	abc	0.00020	0.00005	a
	Average		0.097	0.038	bc	0.0064	0.0043	abc	0.00019	0.00007	b

*Same letter indicates no significant difference at 5 % level.
†This study
‡Cofer et al. (1991)
※Cofer et al. (1998)

Table 4. Gas emissions and global warming potential in different types of forest fire and burning condition in burned area.

Fire type and burning condition	Carbon release† (kg C ha^{-1})	Gas emission CO_2 (kg C ha^{-1}) mean	se	*	CH_4 (kg C ha^{-1}) mean	se	*	N_2O (kg N ha^{-1}) mean	se	*
Fire type										
Crown fire	22500	20387	699	a	130	44	a	3.87	0.035	a
Moderate-severity surface fire	8600	7019	292	e	82	15	a	2.64	0.015	e
Low-severity surface fire	2300	1877	78	f	22	4	b	0.71	0.004	f
Burning condition										
Severe burning condition‡	14290	12674	453	b	94	27	a	2.87	0.023	b
Moderate burning condition※	10120	8664	331	d	79	19	a	2.50	0.017	d
Average	12205	10669	561	c	87	33	ab	2.68	0.028	c

*Same letter indicates no significant difference at 5 % level.
†Conard et al. (2002)
‡Ratio of crown fires : moderate-severity surface fires : low-severity surface fires = 5 : 3 : 2
※Ratio of crown fires : moderate-severity surface fires : low-severity surface fires = 2 : 6 : 2

surface fire (Conard et al., 2002). Then the gas emissions for two fire conditions in burned area, which are moderate burning condition and severe burning condition (Conard et al., 2002), were calculated.

Table 4 shows the results of the calculation. The CO_2 emission accounted for more than 80% of carbon release for all types of forest fire and burning conditions while CH_4 emission accounted for less than 1%. N_2O emission in severe burning condition was larger than that in moderate burning condition because of occurrence of larger N_2O emission in crown fire than ground fire.

3.3 Gas emissions from land covers

The CO_2 emission, which is the negative value of net ecosystem production (NEP), was found to be 1598 kg C ha^{-1} y^{-1} in dry grassland and 1008 kg C ha^{-1} y^{-1} in pond. This indicates that CO_2 production by organic matter decomposition was superior to photosynthetic CO_2 consumption by plants. On the other hand, CO_2 uptake, which is a positive value of NEP, was found to be 388 kg C ha^{-1} y^{-1} in wet grassland and 1400 kg C ha^{-1} y^{-1} in forest. These values of CO_2 emission and uptake in the land covers other than pond were in the range of NEP values in each land cover, which is -1050 to 5400 kg C ha^{-1} y^{-1} in boreal forests (1526 in average and 1947 in standard deviation of 19 data from Amthor et al., 2001; Baldocchi et al., 1997; Griffis et al., 2004; Law et al., 2002; Lloyd et al., 2002; Malhi et al., 1999; Sawamoto et al., 2003), -7500 to 687 kgC ha^{-1} y^{-1} in grasslands (-2337 in average and 2321 in standard deviation of 15 data from Coupland et al., 1979; Gilmanov et al.. 1983; Lohila et al., 2004; Maljanen et al., 2001; Maljanen et al., 2004; Paustian et al., 1990; Reichle et al., 1975; Risser et al., 1995; Soussana et al., 2004; Vourlitis et al., 1999) and -30 to 1642 kg C ha^{-1} y^{-1} in wetlands (481 in average and 404 in standard deviation of 38 data from Alm et al., 1997; Arneth et al., 1999; Aurela et al., 2004; Billett et al., 2004; Heikkinen et al., 2002; Nykänen et al., 2003; Trumbore et al., 1999; Whiting and Chanton, 2001).

The CH_4 emission was found to be 96 kg C ha^{-1} y^{-1} in wet grassland and 237 kg C ha^{-1} y^{-1} in pond, which were in a range of the reported values of 0.353 to 552 kg C ha^{-1} y^{-1} in various boreal wetlands (138 in average and 124 in standard deviation of 37 data from Alm et al., 1997; Alm et al., 1999; Heikkinen et al., 2002; Huttunen et al., 2003; Nykanen et al., 1995; Nykanen et al., 2003; Whalen and Reeburgh, 1988; Whiting and Chanton, 2001).

On the other hand, CH_4 uptake was found to be 0.128 kg C ha^{-1} y^{-1} in forest and 0.068 kg C ha^{-1} y^{-1} in dry grassland. These values were in the lower range compared to the reported values of 0.021 to 2.025 kg C ha^{-1} y^{-1} in boreal forests (0.580 in average and 0.454 in standard deviation of 57 data from Adamsen and King, 1993; Ambus and Christensen, 1995; Ambus et al., 2001; Billings et al., 2000; Bradford et al., 2001; Brumme and Borkan, 1999; Christensen et al., 2001; Dobbie et al., 1996; Gulledge and Schimel, 2000; Klemedtsson and Klemedtsson, 1997; Macdonald et al., 1997; Morishita et al., 2003; Prime et al., 1996; Smith et al., 2000; Whalen et al., 1991).

N_2O emission was found to be 0.009 kg N ha^{-1} y^{-1} in forest. This value was smaller than the reported values ranging from 0.05 to 30 kg N ha^{-1} y^{-1} in various boreal forests (4.35 in average and 7.68 in standard deviation of 15 data from Brumme and Beese, 1992; Brumme et al., 1999; Klemedtsson et al., 2005; Klemedtsson, 1997; Laine et al., 1996; Maljanen et al., 2003; von Arnold et al., 2005). N_2O emissions from dry and wet grasslands were 0.042 and 0.947 kg N ha^{-1} y^{-1}, respectively, which were also low compared to the reported values of boreal forests. The pond showed N_2O uptake of 0.017 kg N ha^{-1} y^{-1} probably due to high water solubility of N_2O.

All values of greenhouse gas emissions measured in different land covers were relatively small compared to the reported values measured in various boreal ecosystems but almost within the range of the reported values. Therefore, we judged that the measured values reflect

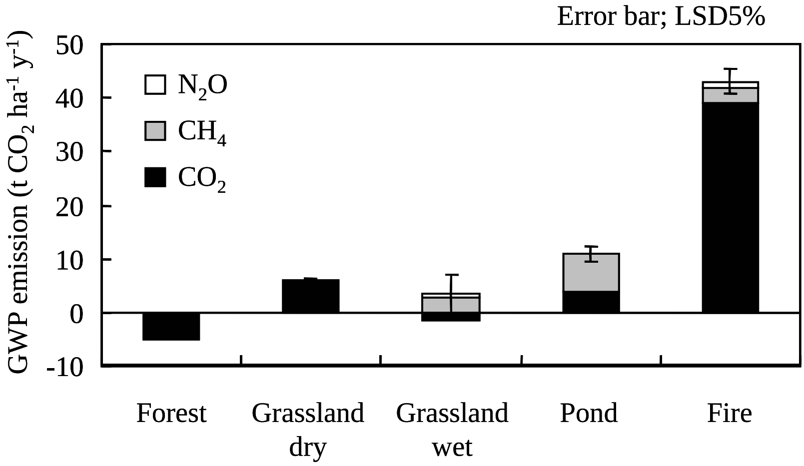

Fig. 1. Global warming potential (GWP) emissions during forest fire and from various land covers.

the characteristics of Central Yakutia and they can be used as representatives to estimate the GWP in Central Yakutia.

3.4 GWP emissions from land covers and during the forest fire

Fig. 1 shows the GWP emissions from land covers and during the forest fire. The total GWP emission during the fire was 43 t CO_2 ha^{-1} y^{-1}, which was significantly higher than those from various land covers. The CO_2 emission during the fire accounted for 91% of the total GWP emissions from fire. The pond showed significantly higher total GWP emission than other ecosystems, which was found to be 11 t CO_2 ha^{-1} y^{-1}. The results revealed that CH_4 emission occupied 65% of the total GWP emissions from the pond.

The GWP emission from wet and dry grasslands was almost similar. However, the GWP emission in wet grassland was composed of mainly CH_4 emissions, while GWP emission in dry grassland was composed of only CO_2 emission. Furthermore, there was a CO_2 uptake in wet grassland. Therefore, the total GWP emission was lower in wet grassland (2 t CO_2 ha^{-1} y^{-1}) than in dry grassland (6 t CO_2 ha^{-1} y^{-1}). Only forest showed a negative GWP emission of -5 t CO_2 ha^{-1} y^{-1}, which indicates that only forests mitigated global warming in Central Yakutia.

3.5 Area of land cover

The result of land cover classification is shown in Table 5. The analyzed total area of land cover was 2604 km^2, of which forests occupied 85.1%. Dry grassland accounted for 8.3%, while ponds and wet grasslands accounted for only 1.9 and 1.2%, respectively. The

Table 5. Land cover distribution in the area of 2604 km^2 which excluded Rena River and its riparian zone from the area of 56 km × 45 km around Yakutsk city.

		Land cover						
		Forest	Grassland dry	Grassland wet	Pond	Others	Total	Burned area*
Area	km^2	2216	217	49	30	91	2604	42
	%	85.1	8.3	1.9	1.2	3.5	100	1.6

*by the proportion of total burned area in 2002 to total area of Republic Sakha (IFFN, 2003)

Table 6. Global warming potential (GWP) from the land area of 2604 km^2 around Yakutsk city.

	GWP emission*											
	CO_2			CH_4			N_2O			Total		
	Mg CO_2 y^{-1}											
		se	†		se	†		se	†		se	†
Forest	-1137765	0	d	-869	727	b	961	438	bc	-1137673	849	d
Grassland, dry	127195	9135	b	-46	13	b	427	78	c	127576	9136	b
Grassland, wet	-7026	17620	c	14530	5665	a	2178	393	b	9682	18512	c
Pond	11105	1234	c	21888	4031	a	-23	8	d	32969	4216	c
Fire	165083	8676	a	11228	4313	a	5267	55	a	181577	9689	a
Total	-841409	21696		46731	8214		8809	596		-785869	23206	

*Negative value indicates gas and GWP uptake by ecosystmes from the atmosphere.
†Same letter indicates no significant difference at 5 % level.

classification accuracy in the forest, dry grassland, and open water was 88, 77, and 97 %, respectively. The overall accuracy was estimated to be 84%. The burned area, which was calculated by the proportion of total burned area in 2002 to the total area of Republic Sakha (IFFN, 2003), was 42 km^2 (1.6%).

3.6 Amounts of gas emission and net GWP emission

Amounts of CO_2, CH_4, and N_2O emission in the 2604 km^2 area are shown in Table 6. Total CO_2 emission of this area showed a negative value of -229 ×10^3 t C, which indicates that the overall area took up CO_2. Forest took up CO_2 of -310 ×10^3 t C which accounted for 99.4% of the total CO_2 uptake. On the other hand, total CO_2 emission in the area was 83 ×10^3 t C, of which fire and dry grassland accounted for 54 and 42 %, respectively. CH_4 budget in the area was 1524 t C. Total CH_4 emission was 1554 t C, which was small as a carbon release from the area of which CH_4 emission from pond, wet grassland and fire accounted for 45.9, 30.5 and 23.6 %. CH_4 uptake was shown in forest and dry grassland, but it was small as 30 t C compared to CH_4 emission. CH_4 uptake in forest accounted for 95.0 % of the total uptake. N_2O emission was 19 t N, of which contribution of fire accounted for 59.6%. N_2O emissions from wet grassland, forest, and dry grassland accounted for 26.0, 10.9, and 4.8 %, respectively. The pond showed a very small N_2O uptake of 0.05 t N.

Fig. 2 shows emissions and uptake of GWP in this area. Net GWP in the area was negative as -781 ×10^3 t CO_2, which indicates that the area was the sink of GWP despite occurrence of forest fire. The total GWP uptake was 1145 ×10^3 t CO_2 and contribution of forest accounted for 99.3% of the total GWP uptake. Other sinks were CO_2 uptake of wet grassland (0.6%) and CH_4 uptake of forest (0.1%). The total GWP emission was found as 364 ×10^3 t CO_2. CO_2 emission during the forest fire and from dry grassland accounted for 45.2 and 34.9 % of the total GWP emission, respectively. CH_4 emission from pond and wet grassland occupied 6.0 and 4.0 %, respectively. Contribution of CH_4 and N_2O emissions during fire was estimated to be 4.6 and 1.4 %, respectively. Other sources were N_2O emissions from wet grassland, forest, and dry grassland (0.6, 0.3 and 0.1 %, respectively).

3.7 Estimation of effect of forest fire

Forest fire was found to be a significant source of GWP emission in Central Yakutia. The

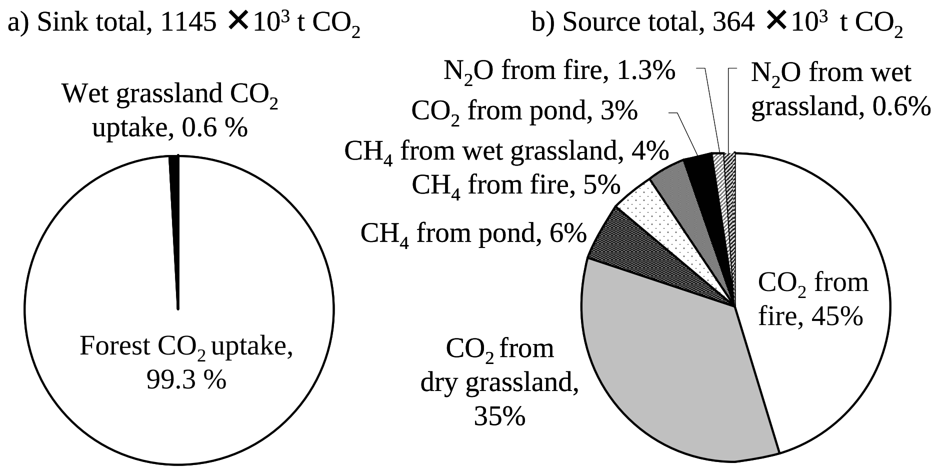

Fig. 2. Proportion of the sinks and sources of global warming potential.

GWP emission rate during fire was estimated to be 43.0 t CO_2 ha^{-1}, which was 8.4 times larger than the GWP uptake rate in the forest (Fig. 1). Fire increases soil temperature by removing the insulating surface organic layer and exposes mineral soil, which may enhance permafrost degradation inducing thermokarst formation (Swanson, 1996; Burn, 1998). However, it also provides a favorable condition for the germination and establishment of some boreal tree species (Landhausser and Wein, 1993). Although there are a lot of uncertainties in the relationship between forest fire and land cover change, forest fire can potentially be an initiator of permafrost degradation.

On the assumption that the burned area becomes wetland (pond and wet grassland) shortly, the relationship between the proportion of burned area and the net GWP emissions during fire (short term effect of forest fire) and the relationship between the proportion of forest and net GWP emissions after fire (long term effect of forest fire) were estimated. The proportion of

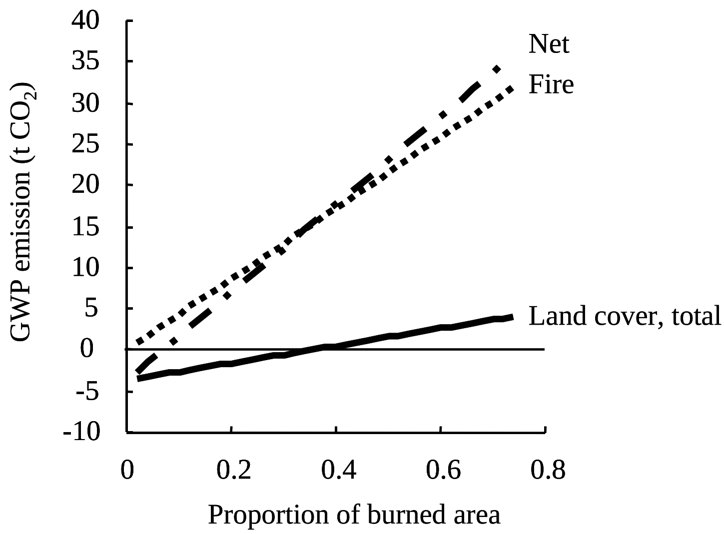

Fig. 3. Effect of forest fire on GWP emissions

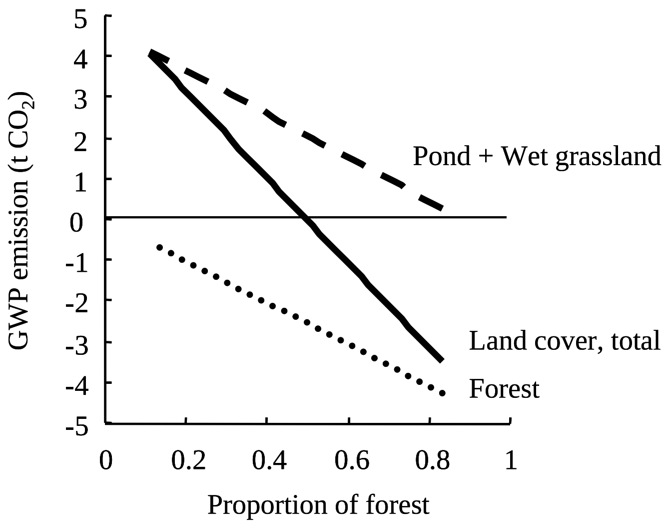

Fig. 4. Relationship between the proportion of forest and GWP emissions in land covers.

pond and wet grassland was assumed to be constant as shown in Table 5.

Fig. 3 shows a short term effect of the forest fire. The estimated net GWP emissions increased with an increase in the proportion of burned area and it became positive after burned area exceeded 7% of the total area.

Fig. 4 shows a long term effect of the forest fire. The net GWP emission increased with a decrease in proportion of forest and it became positive when the forest area became less than 50% of the total area. This is due to a decrease in CO_2 uptake by forest and increase in CH_4 emission from the pond and wet grassland.

4. SUMMARY AND CONCLUSION

By classifying land covers, estimating burned area and performing GWP emission inventories, the net GWP emissions in a total area can be evaluated. Forest fire emitted the highest GWP per unit land area in terms of mainly CO_2 emission during the fire, which is 43 t CO_2 ha^{-1} y^{-1} as 4 times large as GWP emission from the pond, which was the highest emission source among land covers. The GWP emission during the fire accounted for 51% of the total source of GWP emission, although the burned area occupied only 1.6 % of the total area. The GWP emission from dry grassland occupied 35% of the total source of GWP emission, but contribution of the pond was 9%, due to larger area of dry grassland than pond. Improvement of land cover classification, burned area estimation and GWP emission inventories are strongly required for accurate estimation of net GWP emissions. When a forest fire burned more than 7% forest of Central Yakutia, it was estimated that the area as a whole would become a source of GWP emission for a short term. On the other hand, for a long term effect of forest fire on the global warming, there was a big uncertainty for land cover change in the burned area. Only forest was the sink of GWP uptake, therefore the effect of forest fire on global warming would continue after the forest fire occurs. Forest recovery mitigates global warming again, but the thermokarst formation enhances global warming forever. Study on how the process of forest recovery or thermokarst formation would proceed is strongly required for evaluating the long term effect of forest fire on GWP emissions after occurrence of forest fires.

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